THE GERMAN HEAVY ION FUSION PROGRAM

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ABSTRACT

The German Heavy Ion Fusion Program is reviewed. Results obtained in the past funding period have increased our confidence that a heavy ion driver based on the linac/storage ring concept can be built which fulfills the specifications and the conditions of reliability and economics. Many critical issues have been identified which deserve detailed *experimental* studies, to be carried out in the second funding period which started this year. The GSI synchrotron/storage ring facility funded last year will play a crucial role in the future program. In addition, an RFQ high current injector will raise the intensity considerably. The first 5 out of 12 sections are already in operation. With this facility both the interaction of heavy ion beams with dense matter plasmas and beam dynamics issues of the HIBALL driver concept can be investigated.

INTRODUCTION

It was already mentioned by Professor Reiser, that this conference coincides with the 10. anniversary of the first workshop on Heavy Ion Fusion, which was held in Berkeley, July 19-30, 1976, in order to discuss the feasibility of heavy ion beams for inertial confinement fusion and the prospects for a fusion power plant based on a heavy ion driver. This historical event, from which I see many of the old pioneers in the audience, was the igniter for many activities on this subject in some countries, and subsequently some governmental funding programs were established.

Our program in W. Germany started at the end of 1979, and the first six years' funding period expired some months ago, end of 1985. The budget during this time was about 2 M$ per year. Its title was *Studies on the Feasibility of Heavy Ion Beams for Inertial Confinement Fusion* and its goal was two-fold:

1. The identification of key issues of the heavy ion fusion concept, and
2. the experimental and theoretical investigation of some of the issues in the field of accelerator and target physics as far as they could be investigated with existing facilities and with the modest funds available.

This period can be characterized as a first *exploratory approach* to the scientific and technical problems of the heavy ion fusion concept in order to define and pin down the essential issues and difficulties and to find out which direction would be most promising.

Concerning the driver, its realization looked rather straightforward on first sight, and at that time it was considered a more technical rather than scientific challenge. At the end of this first phase things look different now. On the one hand, many important results have been obtained which have increased our confidence that heavy ions are the most promising direction to ICF power generation. On the other hand, crucial physics issues have been revealed, both in the field of accelerator physics as well as in target physics, which necessarily have to be investigated experimentally, before the next major step, the design and construction of a dedicated facility, can be made.

Phase 2 of our program, which already started during the last year, will be dominated, therefore, by experimental activities. Experiments on accelerator issues and on problems of beam-target interaction as well as on matter at high energy density and heavy ion generated dense plasmas, will be the focus of the program. The new synchrotron/storage ring facility of GSI (SIS/ESR) which is funded with 120 M$ to be built in the next four years, will open access to such experiments in the near future (1989).

But even before that date, the recently accomplished first stage of the RFQ injector MAXILAC at GSI can already be used in a limited way for such experiments. In addition, an experiment on beam-plasma interaction is being prepared. All these experiments will be supported by theoretical activities.

The new title of this program is *High Energy Density in Matter Produced by Heavy Ion Beams* and the level of funding is about the same as in previous years. It is our present understanding that only when we will have obtained appropriate experimental information about these problems can we consider to build a dedicated facility in a subsequent phase.

My talk is organized as follows: In the first part I will give a brief account of the major achievements of the first funding period. The second part is devoted to the description of the new GSI facility. Finally, results of the ongoing work will be discussed and the philosophy of the future program and the plans for experiments with the new facilities will be sketched.

1. RESUME OF ACHIEVEMENTS 1979-85

The main emphasis of the research during this period was laid on four different fields:

1. The systems study HIBALL
2. Accelerator and ion source development
3. Theory on beam dynamics and on target issues
4. Experiments on atomic physics issues

All of them were covered in a previous paper[1] and in a brief overview on "Inertial Confinement Fusion with Heavy Ion Beams"[2]. The results and the present status[3] can be summarized as follows:

1. The Systems Study HIBALL. After a concentrated effort during the first two years the HIBALL conceptual design study was finished in 1981.[4] It was based on an rf-linac driver and a liquid first wall of Pb-Li and it was the first study of this kind dealing with all the large components and all the essential aspects of an ICF power station. Its goal was to demonstrate the compatibility of physics and engineering design in the areas of driver, target and reactor chamber through a self-consistent design, and to identify the key problems of this concept.

Based on new results, most of them presented at a workshop in Darmstadt in 1982, an upgrading was started resulting in a new set of the HIBALL parameters. A new report (HIBALL II)[5] including all our present knowledge, was published recently with the following major changes of the driver (Fig. 1):

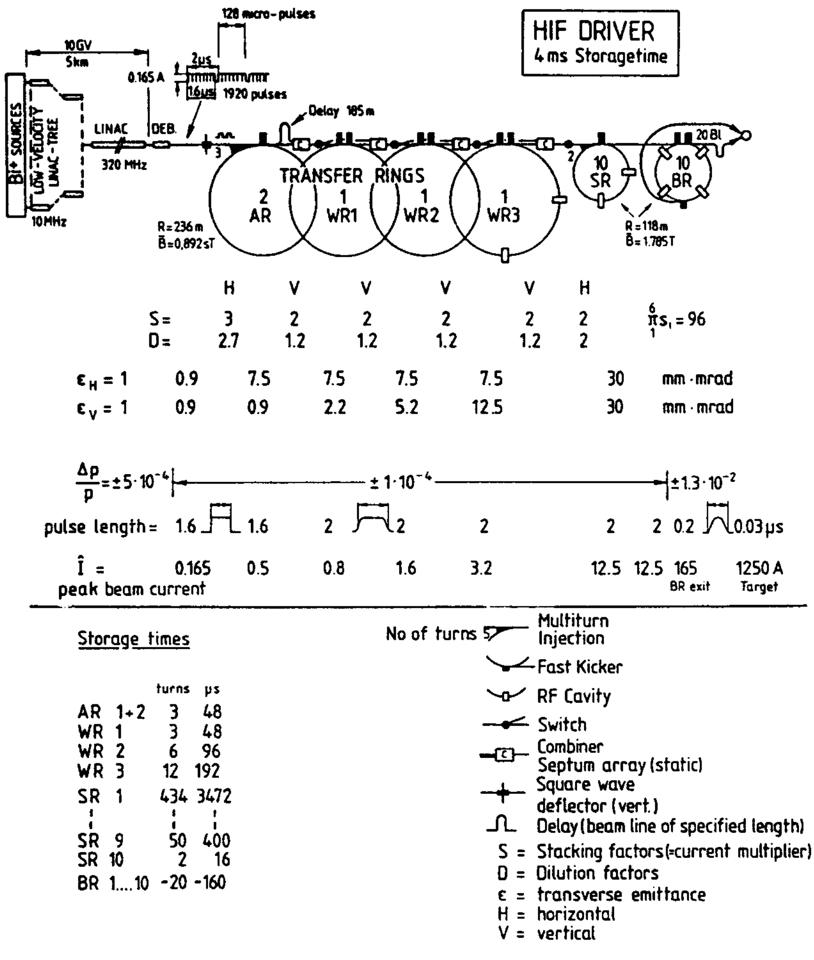

Fig. 1 Concept of the heavy ion fusion driver (HIBALL-II)

a. Because of space charge limitations the double-charged Bi^{2+} was replaced by Bi^{1+}, resulting in a linac of two times the previous length.
b. The storage time in the storage rings had to be reduced by a factor of 10 down to ≤ 4 ms due to micro-wave instabilities.
c. For the final bunching the induction linac bunchers were replaced by buncher rings because of cost considerations.
d. The large "transfer"-ring was changed into several smaller rings because better longitudinal and transverse emittance can be achieved and the momentum blow up during debunching can be omitted.

In our opinion, the HIBALL study has now reached a status in which our present knowledge is taken into account. It will be frozen for some time at the present level until new data will be available allowing a significant improvement.

Among the driver issues investigated during the last period the following deserve further investigations: funneling, beam load in linacs, debunching of the linac beam, microwave instabilities, final bunch compression, prepulse formation, multi-turn stacking.

2. Accelerator and Ion Source Development. The front end of the accelerator, ion source and the low-energy accelerator was considered as one of the key issues of the rf-driver concept. Development of high-brilliance sources was very successful and resulted in high-current heavy ion sources with the necessary small emittance[6]. For the first part of the accelerator, an RFQ structure was chosen and after some prototype development in Frankfurt a full size structure was built at GSI[7]. First results show that the necessary specifications concerning current and emittance can be reached.

3. Theoretical Activities. Systematic work was done in three different fields: Beam dynamics[8], beam-target interaction and target dynamics and design[9].

Beam dynamics studies concentrated on storage and buncher ring issues, where the phase space density is very high and instabilities may occur. Many simulation calculations have been carried out on some topics mentioned before. The beam-target interaction is relevant in particular for the range shortening of energetic heavy ions in plasma, but also other atomic physics problems were investigated, in particular those connected with the planned electron cooling of heavy ions. In target dynamics and target design the situation was more general. In this field we had to get our own experience and our own understanding of the physics involved, therefore a large part of our work was devoted to these problems. Code development and studies on topics such as Rayleigh-Taylor instabilities and the equation-of-state were an important part of our program in the past year.

Most of these activities will be continued also in the next phase of the program but some of them with different weight and some under somewhat changed boundary conditions, namely in closer correlation to the needs of the experiments.

4. Experimental Activities. Some experiments have been carried out, in particular on energy-range correlations for heavy ions in cold matter, an information which was available before only for some selected cases. Systematic and very detailed data have been measured at the UNILAC between 2 and 10 MeV/u for ions up to uranium. In the future this kind of measurements will be continued for hot matter on a much broader scale. Another experiment on ion-ion cross sections at low energy was made with great effort in order to calculate the loss rates for the heavy ion beam in storage rings due to beam-beam interaction. It turned out that the loss rates are not too serious. Also this experiment, because of its importance for the cross section measurements, will be continued with heavier ions. More details will be given in a contribution to this conference and in section 3.

2. THE GSI FACILITIES FOR HEAVY ION FUSION EXPERIMENTS

As reported at the last meeting in Tokyo[1], the German heavy ion fusion community had been discussing for quite some time the question of how to use the heavy ion synchrotron SIS planned at GSI for heavy-ion fusion experiments. The solution found in 1983 was based on the idea of increasing the phase space density of the heavy ion beam by electron cooling in order to approach the phase space limit and to obtain high energy density and high power density by depositing such a beam in matter[10]. An additional storage and cooler ring was designed (SITAR)[11] for this purpose. Achieving high phase space density and the possibility of beam manipulations by this two-ring facility made this project very attractive for heavy ion fusion accelerator and target experiments. The nuclear physics community soon realized the advantages of such a facility for their own research and it was last year that the whole project, now named SIS/ESR[12], was funded and will be finished in 1989/90 at GSI.

The whole new facility will consist of 4 different accelerators: (1) The existing heavy ion linear accelerator UNILAC, (2) the high-current injector MAXILAC, an RFQ structure consisting of about 12 modules, 5 being already in operation, (3) the heavy ion synchrotron SIS of 18 Tm using the UNILAC as an injector and (4) the cooler and storage ring ESR ('ESR' for 'Experimental Storage Ring') of 10 Tm. The UNILAC accelerates already now ions up to uranium to energies up to 20 MeV/u with intensities of about 10^{10} to 10^{12} ions/s limited by the multi-charge ion source (e.g. 8+ for uranium). With an RFQ injector the intensity can be raised by factor of 100 to 1000. The SIS will accelerate heavy ions such as uranium up to about 1 GeV/nucleon. The beam quality can be greatly improved by the ESR, thus providing fine-focussed beams with high intensity and small emittance.

What are the features of this new project with respect to heavy ion fusion and what kind of experiments can be achieved ?

The RFQ High-Current Heavy-Ion Injector

An RFQ structure is particularly appropriate for high-intensity low-velocity acceleration because it has a high focussing power for very slow ions. This feature makes the RFQ structure very attractive for the low-energy end of a heavy ion fusion driver. We decided therefore, some years ago, to develop such a structure in the framework of the German heavy ion fusion program. The design and construction of this RFQ structure has been made at GSI. The special feature of this design (to be used as an injector into UNILAC) is its low rf frequency and the large mass to charge ratio of $A/q \leq 130$. The frequency was chosen half of the Wideröe frequency (13.55 MHz) in order to enable, at a later stage, the operation of two RFQ accelerators in parallel and to combine the two beams by funneling. Though a little more restricted in parameter space than an electrostatically focussed rf linac, this new scheme promised better technical solutions because of the absence of insulators in the high-voltage area.

Most RFQ devices designed for protons use the four-vane structure operating at frequencies of 100 to 400 MHz. For 13.5 MHz this mode is no more adequate. The tanks either get too big or the shunt impedance is too low. A new type of cavity was developed by R.W. Müller (contribution to this conference), which avoids these shortcomings. It is the so-called split coaxial cavity, a TM mode where the magnetic flux inducing the rf voltage toroidally includes the accelerating system which is contained within an inner conductor.

The Darmstadt high-current RFQ injector for UNILAC will consist of about 12 structures of this kind. Five of them are finished and in operation (Fig. 2). The rest will be finished in 1989. With its

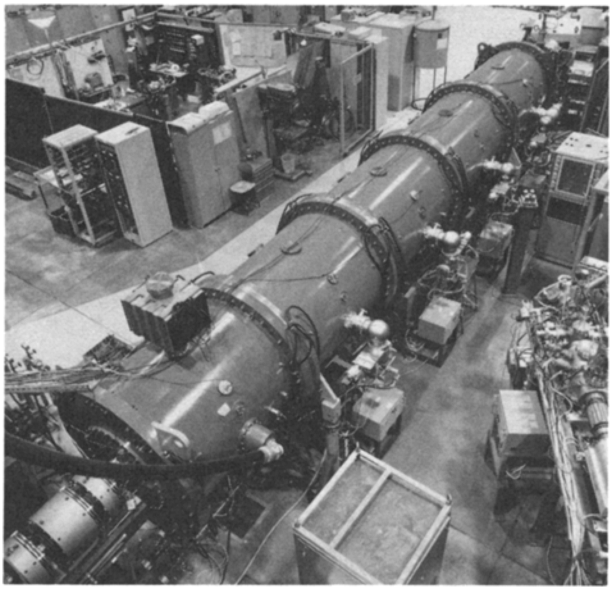

Fig. 2
The first stage of the RFQ injector MAXILAC, consisting of 5 modules (45 keV)

mass-to-charge ratio of 130, singly charged ions up to I^{1+} can be accelerated. The expected space charge limit, occuring when the transverse oscillation frequency is lowered by space-charge forces by 30% is 0.2 x (A/q) mA, e.g. 25 mA for I . If the rf conductivity losses are as designed, 60% of the rf power is transmitted into the beam. The injection energy of the present 5-module accelerator is 2.3 keV/u, the final energy 45 keV/u, the total length 9.5 m. The whole set of five sections came into operation only some months ago, therefore the maximum intensity has not yet been reached. Intensities for various beams are up to about 10 mA. Intensities obtained so far and a set of parameters will be given in another contribution to this conference by R.W. Müller. A schematic view of the whole injector MAXILAC which will be finished in 3 years from now is shown in Fig. 3.

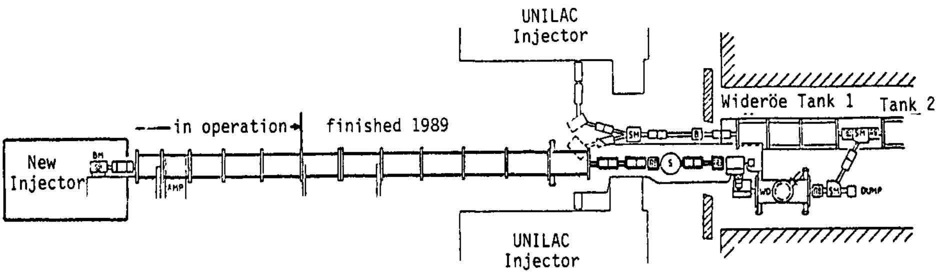

Fig. 3 Scheme of the MAXILAC injector. On the right: Front end of the UNILAC.

The High-Current Heavy Ion Synchrotron/Storage Ring Facility

A synchrotron with a bending power of 18 Tm (SIS 18) is under construction, with MAXILAC and UNILAC as an injector (Fig. 4). The maximum energy of fully stripped uranium ions will be 1.3 GeV/nucleon. The intensities of various heavy ions are given in Fig. 5. The storage and cooler ring (ESR) will be operated in combination with SIS 18. This two-ring accelerator complex shown in Fig. 4 can be used as a test facility for the investigation of accelerator and target issues of heavy ion fusion. In particular many dynamics problems at high space charge density can be investigated.

Due to calculations and simulations, it should be possible to obtain a very small focus spot with the cooled beams and, consequently, very high energy density in a small target volume. The beam diameter should be <0.3 mm and it is expected to reach a power deposition in the target of about 5 TW/g with a pulse length of about 70 ns. If shorter pulses can be achieved (a factor of 3 would be desirable), higher specific power density can be obtained. Some data for heavy ion beam parameters are given in Tab. 1.

After completion this facility will enable the investigation of a number of important target issues relevant to heavy ion fusion, depending on the temperature which can be reached. Fig. 6 exhibits the temperature of the plasma as a function of the specific deposition power. Temperatures up to about 20 eV should be reached and

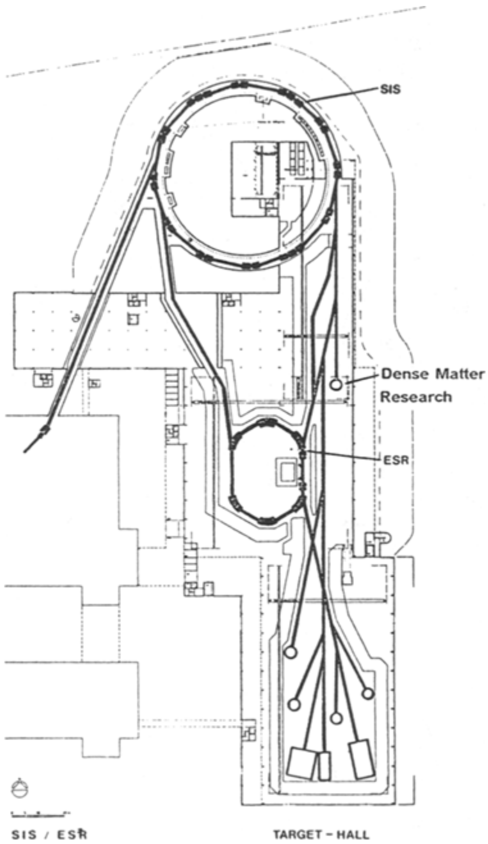

Fig. 4
The SIS/ESR accelerator facility at GSI. The diameter of the synchrotron (SIS) is 65 m. A special area is provided for high-current experiments ('Dense Matter Research')

Tab. 1 SIS/ESR Parameters

Max. SIS Energy for Uranium	1 GeV/u
Ring Diameter (SIS)	65 m
Bending Power	18 Tm
Intensities	
Uranium (at 1 GeV/u)	$4 \cdot 10^{10}$ p/s
(at <500 MeV/u)	10^{11} p/s
Neon (at 1 GeV/u)	$3 \cdot 10^{11}$ p/s
Stored Ions in the ESR	10^{8} - 10^{10} ions
Cooled beams: $\Delta p/p$ ~	$10^{-4} \ldots 10^{-5}$
ε_r ≈	$10^{-6} \ldots 10^{-7}$ π m•rad

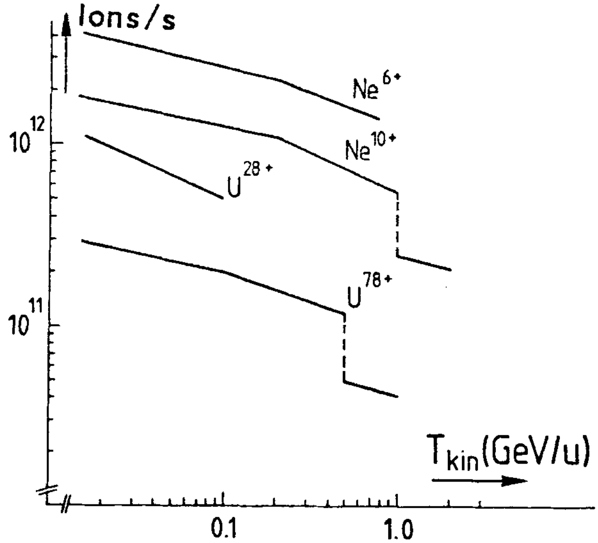

Fig. 5
SIS intensities

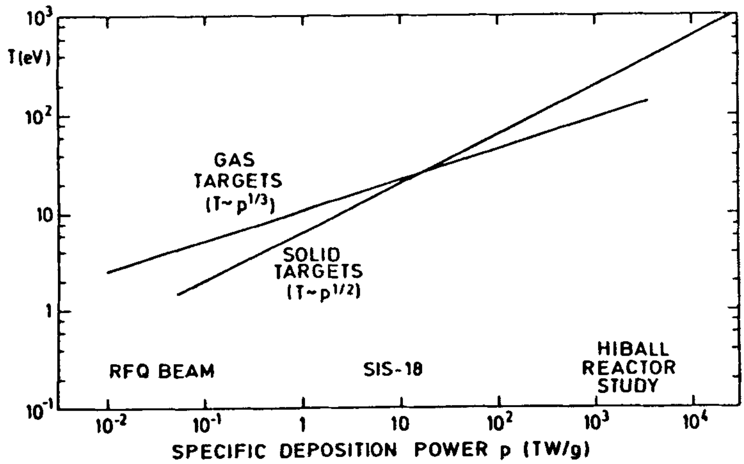

Fig. 6 Temperature reached in a heavy ion beam generated plasma as a function of the specific deposition power

investigations about ion deposition in hot matter, heavy ion generated plasmas, emitted radiation, short wave length laser and the equation-of-state can be carried out.

Comparison between HIBALL and the GSI Test Facility

In the previous section it was pointed out that a large number of problems relevant to heavy ion fusion and to high-current acceleration of heavy ion beams can be investigated with the future GSI facility. Fig. 7 shows the similarity between the HIBALL driver concept and the GSI accelerator complex.

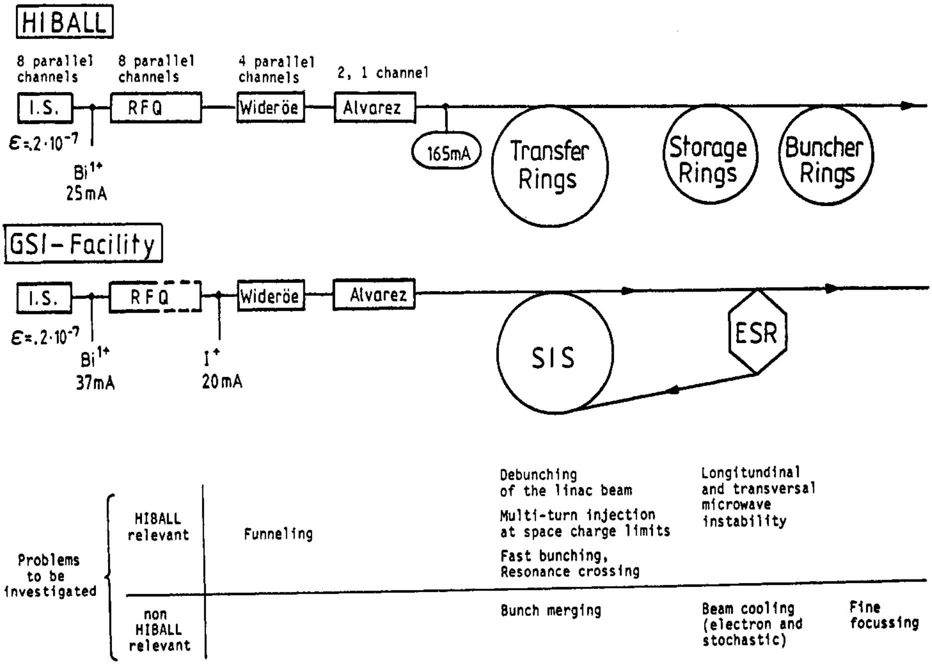

Fig. 7 Comparison between HIBALL and the GSI Accelerator Facility. Some issues which can be investigated with the new facility are given in the lower part of the figure.

Concerning the rf structures, the linac part of the GSI facility is similar to a driver accelerator except the funneling necessary for HIBALL (which might be realized at a later stage). For ion source and RFQ, the part which is already realized at GSI, the HIBALL design values for current and emittance can be reached soon. As mentioned before, the two-ring complex SIS/ESR will allow many HIBALL-relevant problems of beam dynamics to be investigated experimentally, in particular the debunching of the linac beam, multi-turn injection at the space charge limits, fast bunching and resonance crossing, the longitudinal and transversal micro-wave instabilities and fine focussing of heavy ion beams. In addition, a number of non-HIBALL-relevant issues will be investigated, such as bunch merging, electron and stochastic cooling. It is evident that this facility for the first time will provide high-intensity heavy-ion beams for fusion-relevant studies and will comply with the needs for beam handling under such extreme conditions.

3. EXPERIMENTAL ACTIVITIES: PRESENT AND FUTURE

Four different types of experimental activities are going on and will be continued. Some more are in preparation to be carried out at the UNILAC, at the RFQ and, in particular, at SIS/ESR in some years from now.

1. Ion-Ion Charge Exchange

The charge exchange in intra-beam ion-ion collisions due to betatron oscillations is still a key issue for the rf driver/storage ring concept. Most critical are the storage rings because of the long storage time (max. 4 ms). The longitudinal oscillations are negligible, the transversal relative motion is up to 10^6 m/s corresponding to an energy of 130 keV.

A setup for measuring charge exchange cross sections in a crossed beam experiment has been built at Gießen University[13]. Several ion-ion systems have been measured, the heaviest being $Xe^{+}+Xe^{+}$. This is the first measurement of a medium heavy system, in which ionization and capture cross sections have been determined separately in the relevant energy range (Fig. 8).

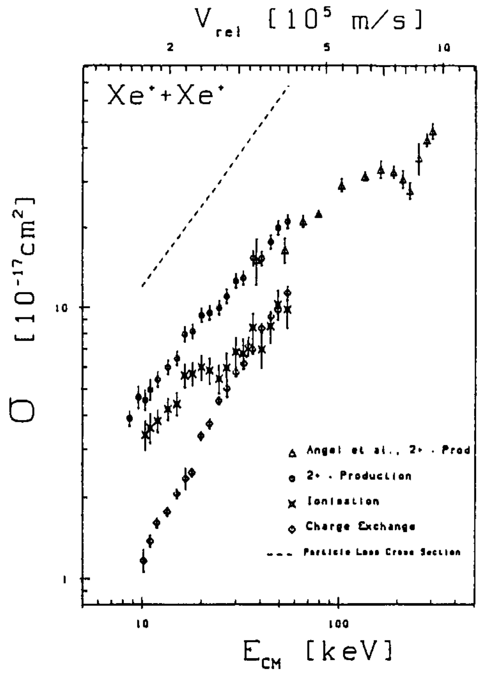

Fig. 8 Cross section for electron capture, ionization and the total Xe^{2+} production in $Xe^{+}+Xe^{+}$ collisions (Salzborn *et al.*, contribution to this conference).

A preliminary calculation of beam losses based on the measured cross sections and on the most unfavourable assumptions concerning the velocity spectrum of the relative motion results in a loss rate of less than 5% for the longest storage time of 4 ms. It is expected that the real loss rates are much smaller. But even a loss of 1% would be a problem. On the other hand the situation for very heavy ions (on which HIBALL is based) might be much different. Consequently an experiment with Bi^{+} on Bi^{+} is in preparation. In these measurements the metastable ions, which can give a large contribution to the cross section, have been separated.

2. Beam-Plasma Interaction

Range shortening in hot matter, predicted by theory[14 15], is a key issue for pellet design. Therefore an experiment for stopping power measurements on heavy ions in plasma is being prepared using the UNILAC beam and a Z-pinch as plasma target. The setup of the Z-Pinch and the diagnostics and measuring devices are shown in Fig. 9. The plasma target is under construction at Aachen University. The line density to be achieved during maximum compression is in the order of 10^{19}cm^{-2} and the dimensions of the fully ionized plasma will be 200 mm in length and 14 mm in diameter. The current rise is designed for 5×10^{12} A/s and the maximum current 8×10^5 A. Before entering the target the beam is deflected by 15^0 in order to use a laser collinear to the ion beam for diagnostics. A second magnet is provided for the analysis of charge states. The experiment will be assembled at the 1.4 MeV/nucleon beam of the UNILAC and should be in operation in 1987.

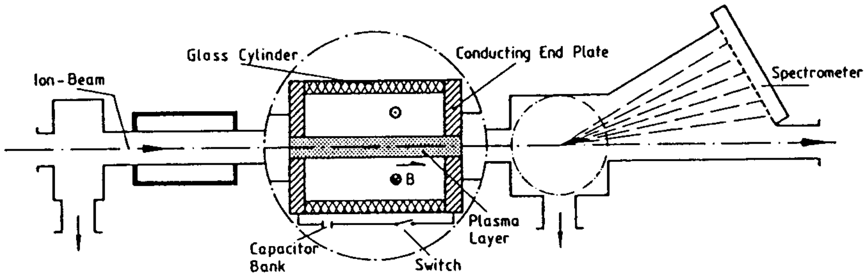

Fig. 9 Conceptual set-up of the Z-pinch experiment to investigate beam-plasma interaction at the 1.4 MeV/u UNILAC beam

In addition, at the RFQ accelerator a beam heated plasma can be produced already now which will be used for the development of diagnostic tools and techniques. Measurements on the time evolution of such a plasma are in preparation, the free electron density being measured by Thomson scattering, the optical spectra by streak cameras. In a gas target of 1 mm in diameter a temperature of a few eV may be obtained.

Another experiment which has been started some years ago at other accelerators[16], the pumping of lasers by heavy ion beams, will be carried out at the new facilities. As the power density is the crucial parameter for getting to shorter wave lengths, the RFQ and later SIS/ESR will provide favourable conditions for pumping excimer lasers.

3. Accelerator Experiments, Theory and Development

The high-current performance of SIS/ESR will for the first time allow a broad spectrum of fusion relevant experimental investigations, in particular those on the manipulation of beams near the space charge limit. Some of the problems to be investigated are already listed in Fig. 7. Most important are the studies on instabilities and emittance growth, for which this two-ring facility provides excellent conditions. During the next three years techniques and concepts for this kind of investigations will be developed.

In this context the ongoing theoretical studies are particularly valuable because they provide the guide lines for these experiments. Present work is focussing on current and phase space density limits in the SIS and ESR. The limitations by intra beam scattering and the resistive microwave instability have been examined for the ESR lattice. Preliminary results indicate that the microwave instability can be overcome by the "stabilizing tail" concept. Work on resonance crossing in the presence of space charge has been extended to a non-linear resonance. In emittance theory a new set of equations has been derived which allows to predict emittance growth in 3 dimensional bunched beams in linacs from excess non-linear field energy. With this theory it has become possible to derive from basic principles the emittance growth in high-current 3d-beams. This work will go on aiming at an experimental verification.

A number of studies is concerned with the electron cooling in the ESR and other issues, not relevant to the fusion driver but very important for the production of high-intensity heavy-ion beams. In this connection an experiment is being prepared to study dielectronic recombination of partially stripped ions as a principal mechanism that limits the lifetime of the ions during cooling.

With a beam transport line, the emittance growth and beam matching has been investigated experimentally and has confirmed the theoretical value of the minimum output emittance for vanishing input emittance[17]. The role of space charge compensation in beam transport has been studied.

Transmission studies with the Frankfurt split coaxial RFQ structure resulted in 85% transmission.

Whereas at GSI the construction of the MAXILAC has been pushed forward and experiments aiming at the improvement of its performance are carried out, the present and future Frankfurt activities cover a broad scope of topics. Some of them are listed in Table 2, and will be covered in more detail in another contribution to this conference.

4. Target Experiments and Target Theory

The important parameter for high-power target experiments is the specific power deposition in matter. What power density can be achieved with this two-ring accelerator and what are the temperatures obtained with this power density ?

Tab. 3 shows a set of parameters for a Iodine beam which is one of several options considered by I. Hofmann[18]. With 10^{11} ions per pulse, an emittance of $\varepsilon = 1.5 \cdot 10^{-6}$m•rad and $\Delta p/p = \pm 4 \cdot 10^{-3}$ a power density of 40 TW/cm^2 should be obtained, resulting in a specific power density of 5 TW/g in solid gold. This number is based on a relatively long pulse length of 70 ns. For target dynamics reasons the optimum pulse length is about 20 ns or less and there are plans for more bunching power, which would raise the power density accordingly.

Tab. 2 Accelerator Development at Frankfurt University
Matching of High Current Beams to the RFQ
Beam Transport Experiments with High Space Charge
Funneling of Particle Beams
Multi Channel Accelerators (RFQ and MEQALAC)
Experimental Investigation of RF-Breakdown Phenomena in Vacuum (Sparking)
Development of Accelerator and Buncher Cavities for the High Current Injector at GSI (MAXILAC)
Beam Neutralisation
Dielectronic Recombination

Tab. 3 Expected Beam Paramaters for High-current Experiments with SIS/ESR	
Ion (as an example)	$^{127}I^{28+}$
Number of Stored Particles	10^{11}
Particle Energy	330 MeV/u
Stored Energy	600 J
Pulse Length	<70 ns
Focal Spot (Diameter)	0.2 mm
Beam Power	12 GW
Power Density	40 TW/cm²
Range in Au	7 g/cm²
Specific Power Density	5 TW/g
Specific Energy	0.25 MJ/g
Plasma Temperature	15 eV

According to simulations with hydrodynamic codes carried out by the group at Garching a temperature of 15 eV should be obtained with 5 TW/g in solid gold. It is expected that under certain conditions temperatures up to 50 eV may be obtained in solid material. Extensive calculations have been made by the Garching group with 1-d and 2-d hydrodynamic codes to get a clear picture of the thermodynamic and hydrodynamic regimes which can be reached with SIS/ESR. Also different target scenarios have been investigated. Fig. 6 shows the predicted temperature dependence as a function of the specific power deposition. It will be discussed in a later talk at this conference by J. Meyer-ter-Vehn. Results on the dynamic behaviour of such a target are shown in Fig. 10.

Several experiments to be carried out with the SIS/ESR beam are discussed at present. One direction will be the investigation of the hydrodynamic and thermodynamic evolution of beam heated targets of various design. Another field, the pumping of short wave length laser will be further pursued. Some new results on temperature scaling of gas targets and on the attempts to reach x-ray lasing conditions look very promising. High-energy heavy ion beams create an elongated needle shaped plasma volume, required for x-ray laser, in a natural way. The crucial question for most of these investigations is whether high enough temperatures can be reached.

Considerations about the experimental set-up have been started, but it is too early to report here on the details of planning. Fig. 11 shows the planned target area at SIS/ESR for these experiments. Its location is shown in Fig. 4.

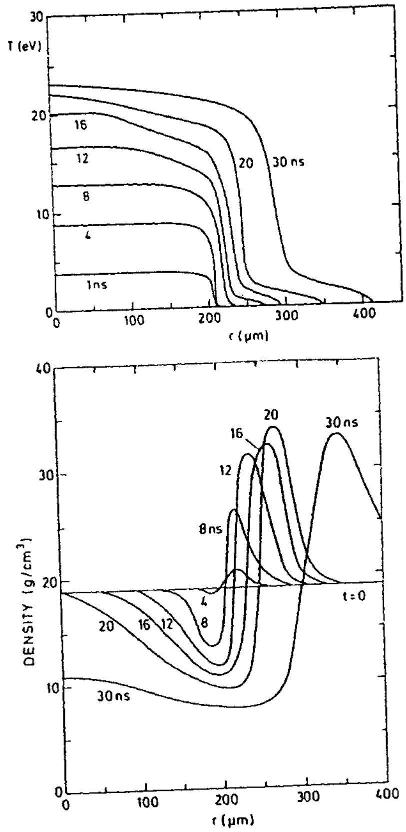

Fig. 10
Temperature and density evolution of a heavy ion beam heated cylindrical target (beam radius 0.2 mm)

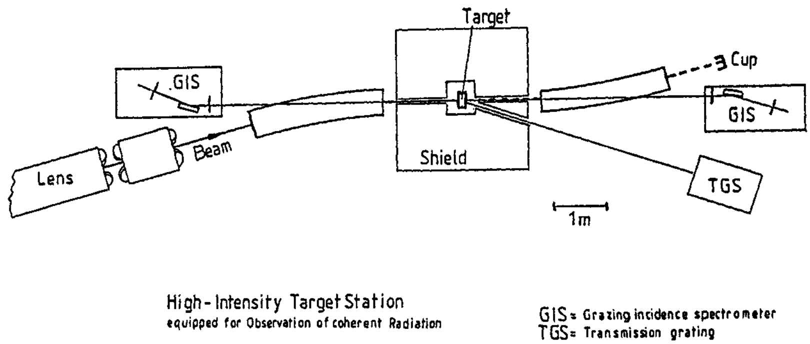

Fig. 11 Planned target area at SIS/ESR for research on high energy density in matter

In conclusion, I would like to emphasize that with the new facilities at GSI a new experimental era for research on fundamental problems of heavy ion physics may evolve and at the same time, based on the results of this phase the further direction of heavy ion fusion can be defined more clearly.

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